

4. Noise Covariance Matrices

Noise Covariance Matrices

Claim Term	CMU's Construction	Marvell's Construction
noise covariance matrices	noise statistics used to calculate the 'correlation-sensitive branch metrics.'	covariance matrices of signal samples (where the signal samples include noise).
'839 Patent Claims 11, 16, 19, 23 '180 Patent Claim 6	CMU Brf. at 27	Marvell Brf. at 27-32

- The Dispute
 - ▶ Does “noise covariance matrices” have its ordinary meaning (Marvell) or has it been re-defined in the patent (CMU)?

Claim Language

- “noise covariance matrices” used to calculate “correlation sensitive branch metrics”

6. A method of detecting a sequence that exploits a correlation between adjacent signal samples for adaptively detecting a sequence of symbols through a communications channel having intersymbol interference, comprising:

- (a) performing sequence detection on a plurality of signal samples using a plurality of correlation sensitive branch metrics;
- (b) outputting a delayed decision on a transmitted symbol;
- (c) outputting a delayed signal sample;
- (d) adaptively updating a plurality of **noise covariance matrices** in response to the delayed signal samples and the delayed decisions;
- (e) recalculating the plurality of correlation sensitive branch metrics from the **noise covariance matrices** using subsequent signal samples; and
- (f) repeating steps (a)–(e) for every new signal sample.

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-continued

$$\begin{aligned} \gamma_k(m', m) &= P(x_k = m | x_{k-1} = m') \\ f_k(x_k | x_{k-1} = m', x_0 = m, z_0, z_1, \dots, z_{k-1}) \\ &= P(x_k = m | x_{k-1} = m') \cdot (2\pi)^{-0.5} e^{-0.5 M_k m^2} \\ \alpha_k(m) &= \sum_{m'=0}^{M-1} \gamma_k(m', m) \alpha_{k-1}(m') \\ \text{For } k &= K-1, K-2, \dots, 0 \\ \beta_k(m) &= \sum_{m'=0}^{M-1} \gamma_{k+1}(m, m') \beta_{k+1}(m') \\ \text{For } k &= 0, 1, \dots, K \\ \lambda_k(m) &= \alpha_k(m) \beta_k(m) \\ \delta_k(m', m) &= \alpha_{k-1}(m') \gamma_k(m', m) \beta_k(m) \end{aligned}$$

Thus, the branch metric, as denoted by the second Equation x, is computed exactly the same way as the metric of Equations 6, 9, 10, 11, and 13. When the process is Gaussian, the branch metric can be computed using Equation 13 and the arrangements described in 3A and 3B.

The generalization of the case described above to a hard output algorithm defined on a trellis or a graph communications (or other dynamic) system. The present invention where the branch metric is computed can be substituted by the metric computation as described in Equations 6, 9, 10, 11, 13 and FIGS. 3A and 3B.

While the present invention has been described in conjunction with preferred embodiments thereof, many modifications and variations will be apparent to those of skill in the art. For example, the present invention is used to detect a sequence that exploits the correlation between adjacent signal samples for adaptively detecting a sequence of symbols through a communications channel having intersymbol interference. The foregoing description and the following claims are intended to cover all such modifications and variations.

What is claimed is:

1. A method of determining branch metric values for a detector, comprising:
receiving a plurality of time variant signal samples having one of signal-dependent correlated noise, and both signal-dependent noise associated therewith;
selecting a branch metric function at a certain time;
and
applying the selected function to the signal samples to determine the metric values.

2. The method of claim 1, wherein the function is selected from a set of signal-metric functions.

3. The method of claim 1, wherein the function is a Viterbi metric function.

4. The method of claim 1, wherein the function is a Generalized Viterbi metric function.

5. The method of claim 1, wherein the function is a Viterbi metric function.

6. A method of detecting a sequence that exploits a correlation between adjacent signal samples for adaptively detecting a sequence of symbols through a communications channel having intersymbol interference, comprising:

(a) performing sequence detection on a plurality of signal samples using a plurality of correlation sensitive branch metrics;

(b) outputting a delayed decision on a transmitted

Specification

- Covariance Matrix C_i used in Correlation-Sensitive Branch Metric Calculation:

With this notation, the general correlation-sensitive metric is:

$$M_i = \log \det \frac{C_i}{\det c_i} + N_i^T C_i^{-1} N_i - n_i^T c_i^{-1} n_i \quad (13)$$

As stated above, the covariance matrix is given as:

$$C_i = \begin{bmatrix} a_i & c_i \\ c_i^T & a_i \end{bmatrix} \quad (14)$$

The matrix $\hat{C}(\Theta, +, -)$ becomes our estimate for the covariance matrix corresponding to this particular symbol sequence (trellis path) and is used to compute the metrics (13) in the subsequent steps of the Viterbi-like algorithm.

$$\hat{C}(\Theta, +, -) = \beta \hat{C}(\Theta, +, -) + (1 - \beta) N N^T \quad (26)$$

$$= \begin{bmatrix} 0.4755 & -0.189 \\ -0.189 & 0.7620 \end{bmatrix}$$

The matrix $\hat{C}(\Theta, +, -)$ becomes our estimate for the covariance matrix corresponding to this particular symbol sequence (trellis path) and is used to compute the metrics (13) in the subsequent steps of the Viterbi-like algorithm.

Specification

- First reference to “the noise covariance matrices”
- Implies the ordinary definition

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METHOD AND APPARATUS FOR
CORRELATION-SENSITIVE ADAPTIVE
SEQUENCE DETECTION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to Provisional 60/046,006, filed May 9, 1997, under 35 U.S.C. 119(e).

STATEMENT REGARDING FEDERAL SPONSORED RESEARCH

This invention was supported in part by the Science Foundation under Grant No. ECD-890. United States Government has certain rights in this.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed generally to magnetic recording sequence detectors, and particularly, to correlation-sensitive sequence detectors.

2. Description of the Background

In recent years, there has been a major shift in of signal detectors in magnetic recording. Traditionally, detectors (PD), such as those described in Nakagawa, "A Study of Detection Methods of NRZ Record," Trans. Magn., vol. 16, pp. 1043-110, Jan. 1980, replaced by Viterbi-like detectors in the form of response maximum likelihood (PRML) schemes between trellis-like detectors and decision feedback equalizers (DFE), such as FDSDF, MHE and FDSDF. These methods were derived under the assumption of additive white Gaussian noise (AWGN) in the system. The resulting trellis/branch metric computed as Euclidean distances.

It has long been observed that the noise in recording systems is neither white nor stationary; stationarity of the media noise results from its signal nature. Combating media noise and its signal nature has thus far been confined to modifying the branch metric to account for these effects. Za "Modified Viterbi Algorithm for Joint-Domain Channel," IEEE Trans. Magn., vol. MAG-28, pp. 1997-2000, Sept. 1992, and Lee et al., "Performance Analysis of Modified Maximum Likelihood Sequence Detection in the Presence of Data-Dependent Noise," Proceedings of the IEEE Conference, pp. 961-964, Oct. 1992 have proposed a branch metric computation method for combating dependent character of media noise. These references refer to the correlation between noise samples. The effect of this method has been demonstrated on real data.

al., "Comparison of Equalization and Detection in High-Density Magnetic Recording," IEEE IN Conference, New Orleans, April 1997.

These methods do not take into consideration correlation between noise samples in the readback signal. Correlations arise due to noise coloring by equalizers, media noise, media nonlinearities, a sensitive (MR) head nonlinearities. This noise causes significant performance degradation at high densities. Thus, there is a need for an adaptive correlation-sensitive maximum likelihood sequence detector which derives the maximum likelihood sequence detector (MLSD) without making the usual simplifying assumption that the noise samples are independent random variables.

SUMMARY OF THE INVENTION

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Because the noise statistics are non-stationary, the noise sensitive branch metrics are adaptively computed by estimating **the noise covariance matrices** from the read-back data. These covariance matrices are different for each branch of the tree/trellis due to the signal dependent structure of the media noise. Because the channel characteristics in magnetic recording vary from track to track, these matrices are tracked on-the-fly, recursively using past samples and previously made detector decisions.

FIG. 12 is an illustration of PR4 detection results at a 2.9 a/symbol, and
 FIG. 13 is an illustration of EPR4 detection results at a 2.9 a/symbol.

'839 patent 2:15-23

CMU's "i.e." Argument Fails

- CMU argues: “By using the abbreviation ‘*i.e.*,’ Latin for ‘that is,’ the CMU patents equated the term ‘noise covariance matrices’ with ‘noise statistics.’”

CMU Brf. at 28

- Fails for Two Reasons:

1. English Usage: “*i.e.*, like *that is*, typically introduces a rewording or clarification of a statement that has just been made or of a word that has just been used”

Webster's Dictionary of English Usage (1989) (Surreply Exh. 1)

- example: “to update my contact information, *i.e.* to update my address”
- “the adaptive nature, *i.e.*, the data dependent nature, of the circuit 52”
‘839 Patent 8:9-10

2. Federal Circuit: “when read in the context of the entire [] patent, the reference to ‘saccharides (*i.e.*, sugars)’ does not constitute a definition of ‘saccharides.’”

Pfizer, Inc. v. Teva Pharmaceuticals, USA, Inc., 429 F.3d 1364 (Fed. Cir. 2005).

CMU's "i.e." Argument Fails

- CMU reads out "covariance matrices" by reading in redundant language ("correlation-sensitive branch metrics")

6. A method of detecting a sequence that exploits a correlation between adjacent signal samples for adaptively detecting a sequence of symbols through a communications channel having intersymbol interference, comprising:

- performing sequence detection on a plurality of signal samples using a plurality of correlation sensitive branch metrics;
- outputting a delayed decision on a transmitted symbol;
- outputting a delayed signal sample;
- adaptively updating a plurality of noise covariance matrices in response to the delayed signal samples and the delayed decisions;
- recalculating the plurality of **correlation sensitive branch metrics** from the noise covariance matrices using subsequent signal samples; and
- repeating steps (a)–(e) for every new signal sample.

statistics used to calculate the correlation-sensitive branch metrics

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-continued
 $\gamma_k(m', m) = P(x_k = m | x_{k-1} = m')$
 $f(x_k | x_{k-1} = m', x_k = m, x_{k-2}, \dots, x_{k-L})$
 $= P(x_k = m | x_{k-1} = m') \cdot (2\pi)^{-0.5} e^{-0.5 M^2 m^2}$
 $a_k(m) = \sum_{m'=0}^{M-1} \gamma_k(m', m) a_{k-1}(m')$
For $k = K-1, K-2, \dots, 0$
 $f_k(m) = \sum_{m'=0}^{M-1} a_{k+1}(m', m) \gamma_{k+1}(m', m)$
For $k = 0, 1, \dots, K$
 $\lambda_k(m) = a_k(m) f_k(m)$
 $\delta_k(m', m) = a_{k+1}(m') \gamma_{k+1}(m', m) f_k(m)$

Thus, the branch metric, as denoted by the second Equation x, is computed exactly the same way as the metric of Equations 6, 9, 10, 11, and 13. When the process is Gaussian, the branch metric can be computed using Equation 13 and the arrangements described in 3A and 3B.

The generalization of the case described above to a hard output algorithm defined on a trellis or a graph communications (or other dynamic) system. The path detector where the branch metric is computed can be substituted by the metric computation as described in Equations 6, 9, 10, 11, 13 and FIGS. 3A and 3B.

While the present invention has been described in conjunction with preferred embodiments thereof, modifications and variations will be apparent to those of skill in the art. For example, the present invention is used to detect a sequence that exploits the correlation between adjacent signal samples for adaptively detecting a sequence of symbols through a communications channel. The foregoing description and the following claims are intended to cover all such modifications and variations.

What is claimed is:

1. A method of determining branch metric values for a detector, comprising:
receiving a plurality of time variant signal samples having one of signal-dependent correlated noise, and both signal-dependent and noise associated therewith;
selecting a branch metric function at a certain time;
and
applying the selected function to the signal samples to determine the metric values.

2. The method of claim 1, wherein the function is selected from a set of signal-dependent metric functions.

3. The method of claim 1, wherein the function is a Viterbi metric function.

4. The method of claim 1, wherein the function is a Generalized Viterbi metric function.

5. The method of claim 1, wherein the function is a Viterbi metric function.

6. A method of detecting a sequence that exploits a correlation between adjacent signal samples for adaptively detecting a sequence of symbols through a communications channel having intersymbol interference, comprising:

(a) performing sequence detection on a plurality of signal samples using a plurality of correlation sensitive branch metrics;

(b) outputting a delayed decision on a transmitted

See '839 Patent Claims 11, 16, 19, 23; '180 Patent Claim 6

CMU's "i.e." Argument Fails

- Re-defining “noise covariance matrices” as “noise statistics” removes “covariance” and “covariance matrices” from the claims
 - ▶ “[a] claim construction that gives meaning to all the terms of the claim is preferred over one that does not do so.”
Merck & Co., Inc. v. Teva Pharm. USA, Inc., 395 F.3d 1364, 1372 (Fed. Cir. 2005).
 - ▶ “covariance” and “covariance matrices” have well-known meanings in engineering and statistics
 - ▶ “covariance” and “covariance matrices” are used independently in other claims

See '839 Patent Claim 10.

CMU's "i.e." Argument Fails

- Patents use “noise covariance matrices” separately from “noise statistics”

Because the **noise statistics** are non-stationary, the noise sensitive branch metrics are adaptively computed by estimating the **noise covariance matrices** from the read-back data. These covariance matrices are different for each branch of the tree/trellis due to the signal dependent structure of the media noise. Because the channel characteristics in mag-

'839 Patent 2:15-23

Computing the branch metrics in (10) or (13) requires knowledge of the signal statistics. **These statistics are the mean signal values m_i in (12) as well as the covariance matrices C_i in (13).** In magnetic recording systems, these

'839 Patent 8:24-27

CMU's "i.e." Argument Fails

- “noise statistics”: used by all branch metrics
- “covariance matrices”: used by only “correlation-sensitive branch metric”

Specific expressions for the branch metrics that result under different assumptions on the noise statistics are next considered.

The factored form of equation (5) is similar to the factored form of equation (10) in the '839 Patent.

'839 Patent 5:56-58

Variance dependent branch metric.

$$M_i = \log \sigma_i^2 + \frac{N_i^2}{\sigma_i^2} = \log \sigma_i^2 + \frac{(r_i - m_i)^2}{\sigma_i^2} \quad (10)$$

The factored form of equation (5) is similar to the factored form of equation (10) in the '839 Patent.

'839 Patent 6:15-34

With this notation, the general correlation-sensitive metric is:

$$M_i = \log \frac{\det C_i}{\det c_i} + N_i^T C_i^{-1} N_i - n_i^T c_i^{-1} n_i \quad (13)$$

normal signal paths are factored as

'839 Patent 6:66-7:4

CMU's "All Embodiments" Argument Fails

- CMU: "Marvell's proposed construction improperly narrows the claims so that they do not encompass all embodiments disclosed in the patents that use 'noise covariance matrices' to compute the correlation-sensitive branch metric."

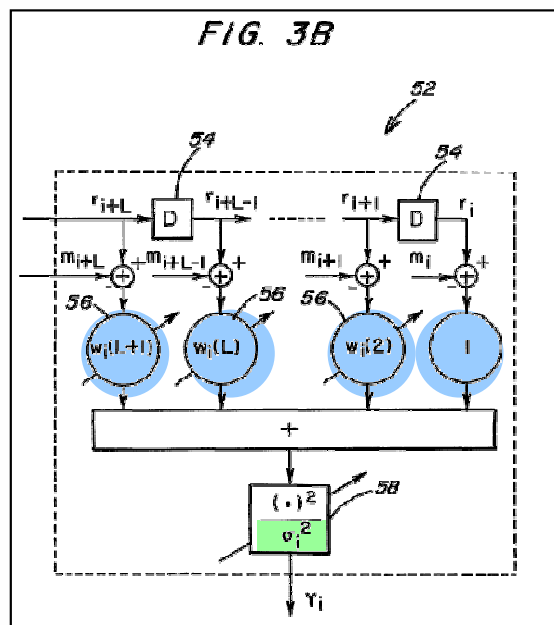
CMU Brf. at 31

- Fails for two reasons:
 1. "[A] claim need not cover all embodiments."
Intamin v. Magnetar, 483 F.3d at 1337 (Fed. Cir. 2007)
 2. Marvell's construction covers all of the embodiments that use covariance matrices

CMU's "All Embodiments" Argument Fails

- CMU: "Specifically, Marvell's construction excludes the tapped-delay line FIR filter embodiment of Figure 3B"
 - ▶ "In this embodiment, the noise statistics used to calculate the branch metrics are the variance σ^2 and the vector of weights w_i ."

CMU Brf. at 31
McLaughlin Decl. (CMU) at ¶ 18



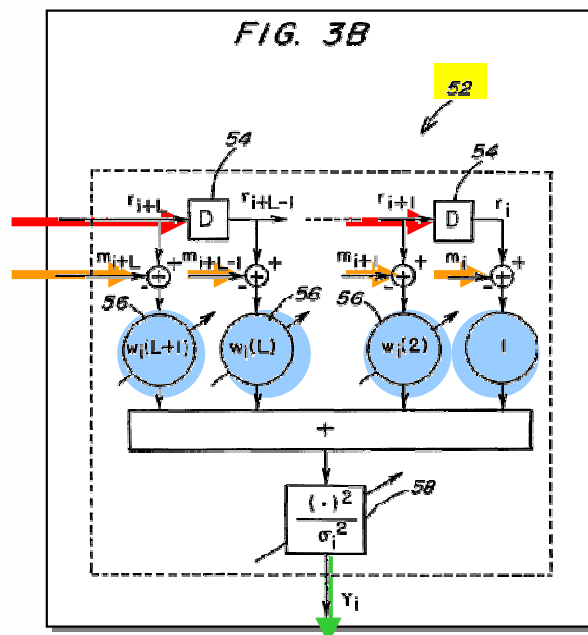
the data dependent nature, of the circuit 52. The weights w_i and the value σ_i^2 can be adapted using three methods. First, w_i and σ_i^2 can be obtained directly from Equations (20) and (16), respectively, once an estimate of the signal-dependent covariance matrix C_i is available. Second, w_i and σ_i^2 can be calculated by performing a Cholesky factorization on the inverse of the covariance matrix C_i . For example, in the $L_i D_i^{-1} L_i^T$ Cholesky factorization, w_i is the first column of the Cholesky factor L_i and σ_i^2 is the first element of the diagonal matrix D_i . Third, w_i and σ_i^2 can be computed directly from the data using a recursive least squares-type algorithm. In the first two methods, an estimate of the covariance matrix is obtained by a recursive least squares algorithm.

839 Patent
8:10-23

- ▶ The patent describes three methods for calculating σ^2 and w_i
- ▶ Marvell's construction covers "the first two methods" (which are the only embodiments described using covariance matrices)

CMU's "All Embodiments" Argument Fails

- The third method (no covariance matrix) corresponds to claims that calculate a "weight w_i " (Group III Claims)
 - These claims do not use "noise covariance matrices"



20. A branch metric computation circuit for generating a branch weight for branches of a trellis for a Viterbi-like detector, wherein the detector is used in a system having Gaussian noise, comprising:

- a logarithmic circuit having for each branch an input responsive to a branch address and an output;
- a plurality of arithmetic circuits each having a first input responsive to a plurality of signal samples, a second input responsive to a plurality of target response values, and an output, wherein each of the arithmetic circuits corresponds to each of the branches;
- a sum circuit having for each branch a first input responsive to said output of said logarithmic circuit, a second input responsive to said output of said arithmetic circuit, and an output.

Equations (17), (18) and (16) (the circuit 52) can be implemented as a tapped-delay line as illustrated in FIG. 3B. The

21. The circuit of claim 20 wherein said branch metric computation circuit is a tapped-delay line circuit with adaptive weight.

'839 Patent 7:61-62

'839 Patent Claims 20-21